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Procedia Engineering 72 (2014) 483 – 488
Procedia Engineering
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The 2014 conference of the International Sports Engineering Association

Development of a new method for the engineering pre-design of sport helmets

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Abstract

Aim of this work is the development and preliminary validation of a method enabling to estimate the theoretical minimum value of the thickness of helmet padding, given the padding preliminary geometry, the energy absorption requirements and the mechanical properties of the material chosen for the development. The approach is based on the close relationship between the absorbed energy and the crushed foam volume of an helmet padding, given the padding curvature and the shape of the contact area at the helmet-anvil interface. Starting from a geometric input such as the head curvature at a certain position, on the basis of the stress-strain curve of a chosen foam, the crushed volume is incrementally increased until the corresponding absorbed energy equals the amount of impact energy transferred to the helmet. The application to a known set of data gave a good correspondence between calculated and measure results, hence encouraging towards a wider validation and its application for obtaining the thickness distribution of a new prototype.

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Keywords: sport helmets; impact tests; thickness; foam padding.

1. Introduction

The development of an innovative helmet in the sport industry is a complex and demanding process that can require large resources and sound experiences in order to obtain a successful result within a sustainable timeline.

Being aware that the success of such a product is nowadays very much conditioned by the style choices, the finishing, the integration with communication technology and the marketing effort in promoting the product, still

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Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University
doi:10.1016/j.proeng.2014.06.085

there is a demand to engineers to perform the structural analysis of the helmet components in order to ensure the meeting of safety requirements, typically oriented to the energy absorption and the penetration resistance properties. The skill required to engineers is to give rapid and correct indications to the style designer for the map of thickness distribution of the padding and the shell of the helmet around the head surface, depending on the materials and technologies adopted for the product. At this pre-design stage, the use of complex tools such as finite element models simulating the impact or of experimental tests on prototypes is not sustainable, as the 3D model of the helmet can not yet be available and the cost of several prototypes can not be affordable.

For this reason, some methods have been proposed in the literature for the theoretical estimation of the minimum thickness of a helmet padding given the field of application (that is the safety standard to comply with), the technology of production, the type of foams that can be adopted for the padding production. The methods developed by Gilchrist & Mills (1994) and by Gibson & Ashby (1997) were clearly described and presented by Shuaeib et al. (2002) and considered in the preparation of the present work. Despite their simplicity, the adoption of the final crushed volume as control volume (named “A” in Shuaeib et al. (2002)) resulted to be the main limitation of the method when applied to available data.

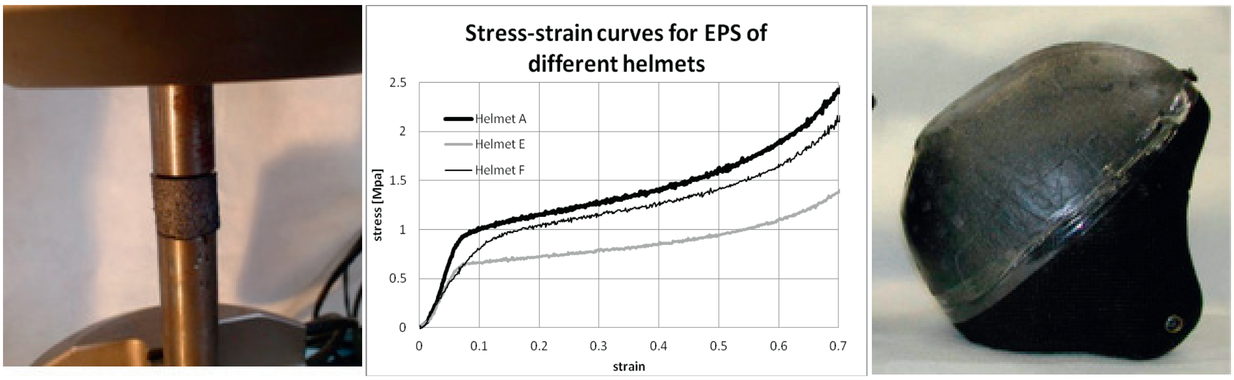
On the other side, the research in this field has developed towards the application and validation of finite element models of the definitive helmet geometry and construction (van de Bosch (2006), Aiello et al.(2007), Cernicchi et al. (2007)): companies and researchers are aware of the amount of effort needed for the modeling, the material characterization, the implementation, the computation and the validation of such virtual models. Eventually, simulations are showing nowadays a degree of accuracy that is costly effective with respect to the experimental testing of prototypes during the product development.

The importance of an accurate pre-design engineering tool to estimate the thickness is however enhanced by the tendency to the reduction of the time-to-market.

Therefore, the focus of the present work was to develop and preliminarily validate a method able to estimate the theoretical minimum value of the thickness of helmet padding, given the padding preliminary geometry, the energy absorption requirements and the mechanical properties of the material chosen for the development.

The analysis was carried out on the basis of previous studies performed at the University of Padova in order to characterize the behaviour of existing ski helmets when subjected to impact. The results which have been taken as a reference had shown how helmets behave in terms of force (and thus, of acceleration) and displacement, when impacting on a flat surface at an average velocity of 5.40 m/s.

In addition to this, cylindrical samples of EPS taken from different helmets had been tested to compression, to verify the influence of different foams (Fig. 1 (a) and (b)). Since the specimens of material had proven to offer the same results of the entire structure, the obtained results could be assumed to represent the behaviour of the whole padding.



(a) (b) (c)

Fig. 1. (a) Compression test on an EPS specimen; (b) stress-strain curves for different kinds of EPS (labelled “A”, “E” and “F” respectively); (c) helmet’s padding after a top impact test.

On the basis of these results, the new analysis has been focused on the development of a theoretical method which could replicate the behaviour of the studied helmets and extend it at the new prototype. Given a geometric feature as an input, precisely the radius of curvature required at a certain position, the method should calculate the minimum thickness that the padding should have to fully absorb a given amount of kinetic energy. As an additional control, the corresponding acceleration should not be greater than 250g, which is the limit prescribed by the standards (UNI EN 13087).

2. Theoretical method

2.1 Ideation

The basis of the developed method is the possibility to correlate the displacement *x* that the padding presents at the impact area to the kinetic energy E_k which is absorbed by the crushed volume of foam. Once this relationship is set, the method should operate an incremental increase of the displacement, starting from zero, until the associated total absorption of energy equals the kinetic energy related to the fall. Thus, from the corresponding value of the displacement *x*, an appropriate thickness for the padding can be set, taking into account the strain at which occurs the typical bottoming out of foams. The developed method, named the "Incremental Method", is schematically presented in Fig. 2.

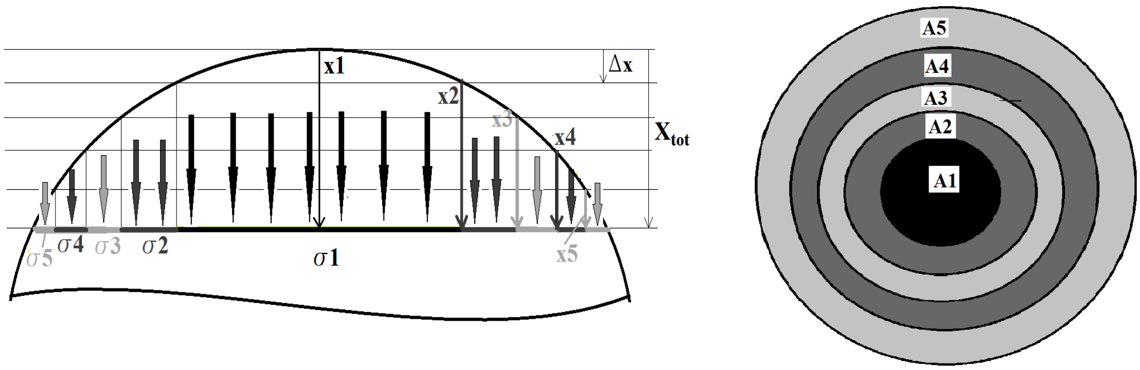


Fig. 2. Scheme of the Incremental Method. At certain values for X_{tot} and D*x* is associated a number of annuli (A1, A2...), each one of whose is subjected to a stress corresponding to the displacement (x1, x2...). The sum of the products s x*A* is the total force acting on the whole area.

According to Hertz theory, the stress acting on the contact area during an impact between a sphere and a flat surface follows a parabolic trend, with the maximum value located at the centre of the contact area. Considering a discrete system, this means that at a certain displacement, or "depth" of crushing, *X*, a stress s *1* corresponding to a displacement *x1* acts on a circular (in the case of a sphere) surface *A1*, a stress s *2* acts on an annulus *A2* that has been compressed of *x2* and so on. Multiplying each stress by the area on which it insists, we obtain a force F_j, which contributes to the definition of the total force *F*, while the sum of the products $F_j\ x_j$ is the energy absorbed so far.

2.2 Implementation

As introduced in the previous paragraph, the method gives an incremental prevision of the total displacement of the helmet in the impact area, stopping when the calculation of the adsorbed energy gives a result equal to the kinetic energy of the impact. The link between geometric and energetic considerations is given by the stress-strain curve of the material constituting the padding, which hence represents one of the inputs to the method. It has to be noticed that, for this work, the engineering curve was used.

The first input needed is the helmet radius of curvature at the impact point. Since the method assumes the considered volume to be spherical, though a helmet has generally a variable curvature, this value will need to be carefully chosen. Another input value is given by D*x*, which according to Fig. 2 controls the accuracy of the schematization and represents the increment unit. Finally, a first assumption has to be made for the thickness of the padding ***t***, in order to compute the strain Dx/t and to enter into the stress strain curve accordingly.

Starting from these data, the calculus creates a series of sections, each one related to an energy-absorption contribution. Referring to Fig. 2, the first step is represented by the case X_{tot} = Dx. Employing a first assumption for the thickness t and considering the engineering quantities, the corresponding deformation is given in Eq. 1:

$$\varepsilon_{ing(1)} = \frac{x_1}{t} \tag{1}$$

The value of the engineering stress s $_{ing}$ is extrapolated from the stress strain curve of the absorbing material. For better implementing the process, the curve has been approximated with a fifth order equation. Once a stress value is calculated, an area is needed to obtain the force contribution associated to the displacement increment Dx. For the first step, the considered area A_1 is circular and is obtained by means of Eq. 2:

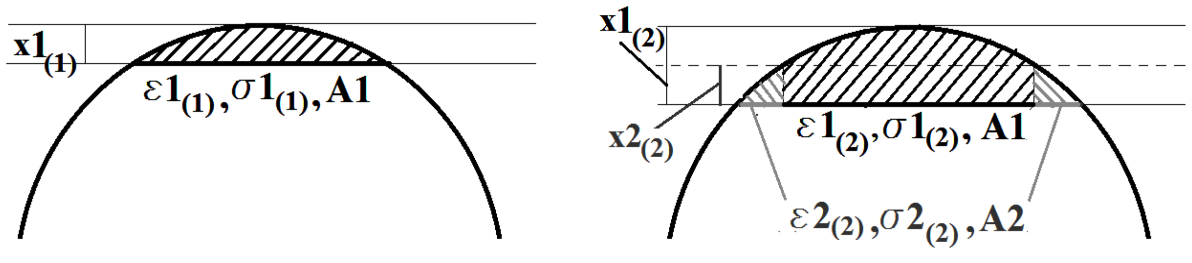
$$A_1 = \pi \cdot a_1^2 = \pi \cdot [R^2 - (R - \Delta x)^2] \tag{2}$$

where R represents the radius assumed for the spherical EPS padding, Dx is the crushing, or displacement, for the first increment and a_1 is the radius of the "flatted surface". The force and energy contributions at step 1 can thus be obtained as follows:

$$F_1 = \sigma_1 \cdot A_1, \tag{3}$$

$$E_1 = F_1 \cdot x_1 \tag{4}$$

Incrementally increasing the total displacement of the padding, i.e. adding new Dx increments, the deformations must be constantly recalculated, since for the Hertz theory the maximum stress corresponds to the centre of the crushed area. For this reason, at a certain step i the central, circular area (labelled as A1 in Fig. 2) is subjected to the maximum value of stress, associated to the maximum deformation so long reached. The outer annuli are subjected to lower values of stress, inversely proportional to their mean radii. A schematization of the process is given in Fig.3, while the Equations needed for the i step of the iteration are presented below:



(a) (b)

Fig. 3. Schematization of the iterative process for a determination of the total crushing of the EPS padding: (a) and (b) represent respectively the first and the second step of the iteration process. It has to be noticed that the deformation 1 remains the highest deformation value for all the process duration, since it always refers to the central portion of the crushed area.

$$\varepsilon_{1(i)} = \frac{x_i}{t},\ \varepsilon_{2(i)} = \frac{x_i - \Delta x}{t}, \quad \ldots,\ \varepsilon_{j(i)} = \frac{x_i - (j-1)\cdot \Delta x}{t}, \quad i = 1, \ldots, i^* \tag{5}$$

$$A_j = \pi \cdot [R^2 - (R - j \cdot \Delta x)^2] - \sum_{k=1}^{j-1} A_k \ , \qquad j = 2,...,i \qquad i = 1,...i^* \tag{6}$$

Proceeding with the iterations, the generated force and the amount of absorbed energy can be calculated for each step as the sum of the contributions F_j and E_j respectively (Eqs. 7-8):

$$F_i = \sum_{j=1}^{i} F_j = \sum_{j=1}^{i} \sigma_j \cdot A_j \qquad i = 1,...i^* \tag{7}$$

$$E_i = \sum_{j=1}^{i} E_j = \sum_{j=1}^{i} F_j \cdot x_j \qquad i = 1,...i^* \tag{8}$$

The computation proceeds until the iteration i^* ,when the value E_i defined in Eq. 8 reaches the amount of kinetic energy E_k which has to be absorbed by the padding ($E_{i^*} = E_k$): this can be equal to the whole kinetic energy of the falling mass, if the outer shell plays no role in the energy absorption, or to an opportune percentage, if the shell presents absorbing properties itself. According to the current standards, the total force generated during the crushing must not exceed the force threshold corresponding to an acceleration of 250 g. If this requisite is satisfied, then the assumed thickness can be successfully associated to the considered curvature radius. Nevertheless, for a complete design process, several attempts have to be done in order to find the minimum thickness obtainable.

3. Validation and Conclusions

The Incremental Method has been validated against a set of known parameters coming from a real impact test on a padding, in order to compare the results and validate the process. The event which has been taken as reference was the top impact of a standard headform (size 605 according to UNI EN 960) wearing the EPS padding of a helmet (model labelled as “E” in Fig.1). An overall mass of about 5.5 kg fell from a height of 1.5 m, hitting a flat anvil at an approximate velocity of 5.4 m/s and with a kinetic energy of about 80.5 J. At the impact point, located on the top of the helmet, the padding presented a thickness of 20 mm and an almost-spherical profile with a curvature radius of 145 mm. The results obtained with these parameters have been compared with the output of a load cell mounted on the anvil and a triaxial accelerometer mounted on the headform, with particular attention to the maximum displacement at the impact area during the contact obtained after integration of the headform acceleration. As an additional comparison, a new acceleration value has been obtained from the formula presented by Gilchrist and Mills for the generated force, which considers a constant value for the foam yield stress s_y :

$$F \cong 2\pi R_h \sigma_y x \tag{9}$$

where R_h is the external radius of the impacting body and x is the central deflection, or displacement, of the foam.

As shown in Table 1, the Incremental Method is quite successful in predicting the behaviour of the EPS padding, with an error of about 4% on the total displacement and 8% on the peak acceleration.

Since the acceleration was over-estimated by the computational method, no correction has been applied to the results, in order to leave a safety margin for the thickness distribution. Subsequently, the method can be employed to generate a distribution for the minimum thickness all over the surface of the standard UNI headform.

Table 1. Comparison of the impact test maximum displacements and peak acceleration estimated with the Incremental Method and with the Gilchrist-Mills' formula (9).

	Impact test	Incremental Method	Gilchrist-Mills
Maximum displacement [mm]	17.09	16.36	N.A.
Acceleration peak [g]	197.18	213.14	227.8

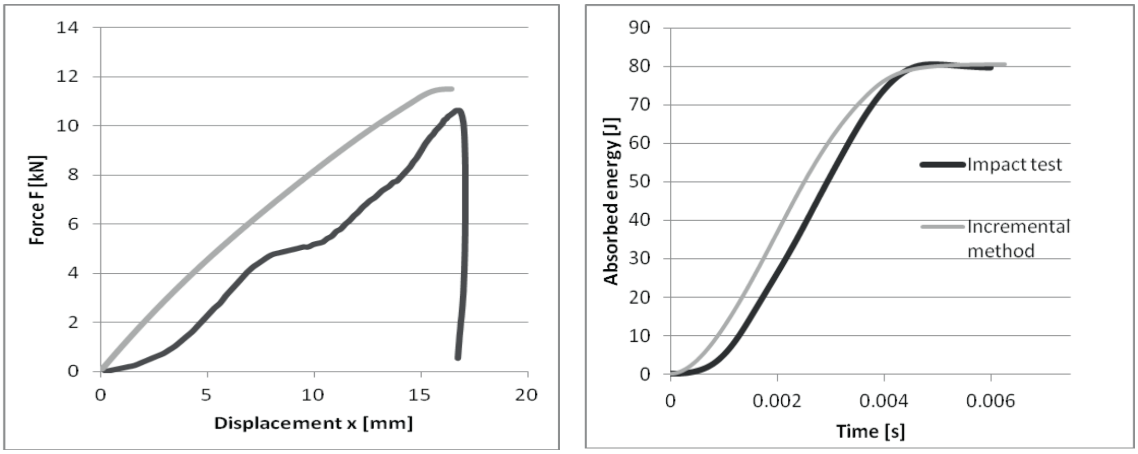


Fig. 4. Comparison between experimental and theoretical results in terms of force-displacement (a) and energy-time (b) curves.

The incremental progress of the illustrated method is shown in Fig. 4, in which an additional comparison is made between experimental and theoretical results. Although different in trend, the Force-displacement curve presents a good correspondence for what concerns the total displacement and the maximum force peak, while a better matching between the curves can be detected in the Energy-time graph.

On the basis of the presented results, the method implemented seems suitable for the application to different materials and helmet shapes: its validation over a wider range of materials, shapes, speeds and masses is needed to allow its application in the pre-design of sport helmet padding.

Acknowledgements

The work was conducted within the Interreg IV project "Safe-A-Head", Nr. 5064-781.

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